

## SONET CAPABLE MILLIMETER WAVE COMMUNICATION SYSTEM

The present invention relates to communication systems and specifically to fixed wireless communication systems. This application is a continuation-in-part application of Serial No. 09/847,629 filed May 2, 2001, Serial No. 09/872,542 filed June 2, 2001, Serial No. 09/872,621 filed June 2, 2001, Serial No. 09/882,482 filed June 14, 2001, Serial No. 09/952,591, filed September 14, 2001, Serial No. 09/965,875 filed September 28, 2001, Serial No. \_\_\_\_\_ filed October 25, 2001, Serial No. 10/001,617 filed October 30, 2001, Serial No. 09/992,251 filed November 13, 2001, and Serial No. 10/000,182 filed December 1, 2001 all of which are incorporated herein by reference.

### BACKGROUND OF THE INVENTION

#### Wireless Communication

##### Point-to-Point and Point-to-Multi-Point

Wireless communications links, using portions of the electromagnetic spectrum, are well known. Most such wireless communication at least in terms of data transmitted is one way, point to multi-point, which includes commercial radio and television. However there are many examples of point-to-point wireless communication. Mobile telephone systems that have recently become very popular are examples of low-data-rate, point-to-point communication. Microwave transmitters on telephone system trunk lines are another example of prior art, point-to-point wireless communication at much higher data rates. The prior art includes a few examples of point-to-point laser communication at infrared and visible wavelengths.

#### Need for High Volume Information Transmission

The need for faster (i.e., higher volume per unit time) information transmission is growing rapidly. Today and into the foreseeable future transmission of information is and will be digital with volume measured in bits per second. To transmit a typical telephone conversation digitally utilizes about 5,000 bits per second (5 Kbits per second). Typical personal computer modems connected to the Internet operate at, for example, 56 Kbits

per second. Music can be transmitted point to point in real time with good quality using MP3 technology at digital data rates of 64 Kbits per second. Video can be transmitted in real time at data rates of about 5 million bits per second (5 Mbits per second). Broadcast quality video is typically at 45 or 90 Mbps. Companies (such as telephone and cable companies) providing point-to-point communication services build trunk lines to serve as parts of communication links for their point-to-point customers. These trunk lines typically carry hundreds or thousands of messages simultaneously using multiplexing techniques. Thus, high volume trunk lines must be able to transmit in the gigabit (billion bits, Gbits, per second) range. Most modern trunk lines utilize fiber optic lines. A typical fiber optic line can carry about 2 to 10 Gbits per second and many separate fibers can be included in a trunk line so that fiber optic trunk lines can be designed and constructed to carry any volume of information desired virtually without limit. However, the construction of fiber optic trunk lines is expensive (sometimes very expensive) and the design and the construction of these lines can often take many months especially if the route is over private property or produces environmental controversy. Often the expected revenue from the potential users of a particular trunk line under consideration does not justify the cost of the fiber optic trunk line. Digital microwave communication has been available since the mid-1970's. Service in the 18-23 GHz radio spectrum is called "short-haul microwave" providing point-to-point service operating between 2 and 7 miles and supporting between four to eight T1 links (each at 1.544 Mbps). Recently, microwave systems operation in the 11 to 38 GHz band have reportably been designed to transmit at rates up to 155 Mbps (which is a standard transmit frequency known as "OC-3 Standard") using high order modulation schemes.

#### Data Rate vs. Frequency

Bandwidth-efficient modulation schemes allow, as a general rule, transmission of data at rates of 1 to 10 bits per Hz of available bandwidth in spectral ranges including radio wave lengths to microwave wavelengths. Data transmission requirements of 1 to tens of Gbps thus would require hundreds of MHz of available bandwidth for transmission. Equitable sharing of the frequency spectrum between radio, television, telephone, emergency services, military and other services typically limits specific frequency band allocations

to about 10% fractional bandwidth (i.e., range of frequencies equal to about 10% of center frequency). AM radio, at almost 100% fractional bandwidth (550 to 1650 GHz) is an anomaly; FM radio, at 20% fractional bandwidth, is also atypical compared to more recent frequency allocations, which rarely exceed 10% fractional bandwidth.

### Reliability Requirements

Reliability typically required for wireless data transmission is very high, consistent with that required for hardwired links including fiber optics. Typical specifications for error rates are less than one bit in ten billion ( $10^{-10}$  bit-error rates), and link availability of 99.999% (5 minutes of down time per year). This necessitates all-weather link operability, in fog and snow, and at rain rates up to 100 mm/hour in many areas.

### Weather Conditions

In conjunction with the above availability requirements, weather-related attenuation limits the useful range of wireless data transmission at all wavelengths shorter than the very long radio waves. Typical ranges in a heavy rainstorm for optical links (i.e., laser communication links) are 100 meters and for microwave links, 10,000 meters.

Atmospheric attenuation of electromagnetic radiation increases generally with frequency in the microwave and millimeter-wave bands. However, excitation of rotational transitions in oxygen and water vapor molecules absorbs radiation preferentially in bands near 60 and 118 GHz (oxygen) and near 23 and 183 GHz (water vapor). Rain, which attenuates through large-angle scattering, increases monotonically with frequency from 3 to nearly 200 GHz. At the higher, millimeter-wave frequencies, (i.e., 30 GHz to 300 GHz corresponding to wavelengths of 1.0 millimeter to 1.0 centimeter) where available bandwidth is highest, rain attenuation in very bad weather limits reliable wireless link performance to distances of 1 mile or less. At microwave frequencies near and below 10 GHz, link distances to 10 miles can be achieved even in heavy rain with high reliability, but the available bandwidth is much lower.

## Last Mile

Much attention by the communication industry has been given recently to the challenge of providing equipment that will permit individual users to connect easily and inexpensively to high data rate communication links such as fiber optic trunk lines. This challenge is referred to as the "last mile" challenge. Most individual electronic communication is via telephones through telephone lines in which pairs of copper wire connect the users' telephone to a telephone company's switching equipment. The circuit is basically the same two-wire circuit used by the Bell system since the 1890's. This pair of wires may be (especially if the facility was built or updated relatively recently) a twisted pair. (Since multiple strands of twisted wire can be installed easily and inexpensively if installed when the premises is constructed, many premises are provided with several sets of twisted pairs running to various locations on the premises.) Typically, the telephone equipment at both ends of these telephone lines (i.e., at the users telephone and at the telephone company's switching equipment) is analog and analog information is transmitted over this "last mile". This "last mile" may be a few feet or many miles. These analog circuits cannot carry digital information since they were designed to carry voice. In these circuits the strength and frequency of the signal depend on the volume and the pitch of the sounds being sent. In order for computers to communicate using these lines the typical procedure is to convert the computer's information into on and off analog tones that can be transmitted over the old fashion telephone circuit. This is done with a modem such as the Bell 103 modem that operated at a speed of 300 bits per second. More modern modems can transmit information in this manner at rates of 57,000 bits per second. The copper pair could be replaced with fiber optic lines or coaxial cable greatly increasing communication speed but to do this for thousands or millions of users would be extremely expensive.

## DSL

A solution to this last-mile problem that is available in many cases is a technology recently developed which adapts the copper pair to transmit digital data. The line once converted is known as a Digital Subscriber Line (DSL). Typically a DSL access module is installed in the telephone company switching station which divides the available

frequency spectrum on each telephone line reserving about 4 KHz of the lowest spectrum for existing analog telephone and FAX use. The remaining range of available frequency spectrum is devoted to digital data transmission. Typically, the systems are arranged so that much greater data rates are provided toward the user than from the user back to the telephone switching station. This type of service is called an Asynchronous Digital Subscriber Line (ADSL). With typical ADSL lines downstream data rates in the range of about 1.5 to 9 Mbps and upstream data rates of about 16 to 640 Kbps can be achieved. The possible data rate is largely dependent on the length of the pair of conductors with the limit being about 3.5 miles. Recently, technology has been developed for greatly increasing the potential data transmission rates using twisted pair links. Rates as high as 55 Mbps are possible. However, the technology works only at short distances such as less than about 1000 feet. Downstream speeds of 13 Mbps can be provided at distances in the range of up to 4,000 feet. For these Very high rate Digital Subscriber Line (VDSL) systems upstream rates of 1.6 to 2.3 Mbps are typical. In addition to ADSL and VDSL, DSL comes in a number of variants, the total range of which are generally referred to as xDSL.

### Ethernet

The term Ethernet refers to a family of local area network implementations that includes three principal categories that are governed by industry specifications to operate at data rates of: 10 Mbps, 100 Mbps and 1000 Mbps, respectively. These Ethernet implementations are well known and are described in many available network texts such as Internetworking Technologies Handbook, Second Edition, Published by Cisco Press, Macmillan Technical Publishing, Indianapolis, Indiana, p. 87 –124.

What is needed is a wireless data link that can provide trunk line data rates in excess of 1 Gbps over distances up to ten miles in all weather conditions except the most severe, with beam widths narrow enough so that an almost unlimited number of users can communicate using the same frequency bands combined with a network for dividing that data transmission capacity among many users so that each of the users can have available to him at high digital data rates.

## SONET and Multi-Protocol Data Aggregation

Synchronous optical network (SONET) is a standard for optical telecommunications transport formulated by the Exchange Carriers Standards Association (ECSA) for the American National Standards Institute (ANSI), which sets industry standards in the U.S. for telecommunications and other industries. The comprehensive SONET standard is expected to provide the transport infrastructure for worldwide telecommunications for at least the next two or three decades. SONET implementations are well known and are described in many available network texts such Understanding SONET/SDH and ATM: Communications Networks for the Next Millennium, Stamatios V. Kartalopoulos by Wiley-IEEE Press.

Business customers present various challenges for the efficient delivery of telecom and datacom services. A wide variety of necessary service types include voice, data, storage, and private line services with ever increasing bandwidth consumption. Equipment needs to be deployed cost effectively at the customer premise with a high-speed connection to the central office. Multiple business locations within a metropolitan market create a need for intelligent traffic aggregation and high-speed transport to adequately cope with the amount and variety of services consumed.

Historically, service providers have been forced to meet large customer and multi-tenant building service and bandwidth needs using a combination of interoffice transport equipment and one or more access platforms. This architecture is less than optimal because interoffice transport equipment supports only a limited number of service interfaces and has little or no capability to aggregate packet traffic, while access equipment cannot offer sufficient bandwidth to the metropolitan fiber infrastructure. The result of these limitations is: poorly utilized fiber assets, excessive equipment requirements at the service provider's central office or point of presence (POP), excessive premise equipment requirements, overlaid networks in the access: TDM, ATM, IP, etc., and overly complex network management. Because customer demand is never assured in either quantity or type of service, much of the prior art multi-box solution is underutilized. To meet subscribers' bandwidth and service needs, providers need a highly

scalable voice and data solution able to operate with all major network protocols simultaneously and to link these data streams at gigabit per second rates.

What is therefore needed is an affordable gigabit wireless data-link based network that can aggregate all major network protocols simultaneously and operate with SONET networks.

### **SUMMARY OF THE INVENTION**

The present invention provides a point-to-point, wireless, millimeter wave trunk line communications link at high data rates in excess of 1 Gbps and at ranges of several miles during normal weather conditions to connect a local communication network through a SONET aggregation unit to a high speed fiber-optics network. In a preferred embodiment a trunk line communication link operates within the 92 to 95 GHz portion of the millimeter spectrum. A first transceiver transmits at a first bandwidth and receives at a second bandwidth both within the above spectral range. A second transceiver transmits at the second bandwidth and receives at the first bandwidth. The transceivers are equipped with antennas providing beam divergence small enough to ensure efficient spatial and directional partitioning of the data channels so that an almost unlimited number of transceivers will be able to simultaneously use the same spectrum. Antennas and rigid support towers are described to maintain beam directional stability to less than one-half the half-power beam width. In a preferred embodiment the first and second spectral ranges are 92.3-93.2 GHz and 94.1-95.0 GHz and the half power beam width is about 0.36 degrees or less. Preferred embodiments utilize an Ethernet providing data communication among switch banks at 1 gigabits per second and communication among a large number of users at 100 Mbps.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 is a schematic diagram of a millimeter-wave transmitter of a prototype transceiver system built and tested by Applicants.

FIG. 2 is a schematic diagram of a millimeter-wave receiver of a prototype transceiver system built and tested by Applicants.

FIG. 3 is measured receiver output voltage from the prototype transceiver at a transmitted bit rate of 200 Mbps.

FIG. 4 is the same waveform as FIG. 3, with the bit rate increased to 1.25 Gbps.

<sup>561, and 562</sup>  
FIGS. 5A ~~and 5B~~ are schematic diagrams of a millimeter-wave transmitter and receiver in one transceiver of a preferred embodiment of the present invention.

<sup>601, and 602</sup>  
FIG. 6A ~~and 6B~~ are schematic diagrams of a millimeter-wave transmitter and receiver in a complementary transceiver of a preferred embodiment of the present invention.

FIGS. 7A and 7B show the spectral diagrams for a preferred embodiment of the present invention.

FIG. 8 is a layout showing an installation using a preferred embodiment of the present invention.

FIGS. 9 and 9A show a preferred hollow steel tube antenna support structure (diameter of 24 inches) rigid enough for use in a preferred embodiment of the present invention.

FIG. 10 shows how very slight directional instability can interfere with transmission.

FIG. 11 is a drawing showing a preferred embodiment for providing high data rate communication service to a remote hotel using DSL equipment.

FIG. 12 is a drawing showing a preferred embodiment similar to the FIG. 11 embodiment but using less expensive Ethernet equipment.



FIG. 13 is a drawing showing a preferred embodiment similar to the FIG. 12 embodiment but providing 100Mbps service to more than 100 workspaces.

FIG. 14 is a drawing showing a preferred embodiment with an aggregation unit and one or more high-speed wireless links providing access (to the optical core) and traffic grooming for a wide variety of different telecommunications protocols at a customer's premises.

FIG. 15 is a drawing showing a preferred embodiment with an aggregation unit and several high-speed wireless links providing access (to a SONET ring) and traffic grooming for a wide variety of different telecommunications protocols at a variety of different customer's premises.

## **DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS**

### **Prototype Demonstration**

A prototype demonstration of the millimeter-wave transmitter and receiver useful for the present invention is described by reference to FIGS. 1 to 4. With this embodiment the Applicants have demonstrated digital data transmission in the 93 to 97 GHz range at 1.25 Gbps with a bit error rate below  $10^{-12}$ .

The circuit diagram for the millimeter-wave transmitter is shown in FIG. 1. Voltage-controlled microwave oscillator 1, Westec Model VTS133/V4, is tuned to transmit at 10 GHz, attenuated by 16 dB with coaxial attenuators 2 and 3, and divided into two channels in two-way power divider 4. A digital modulation signal is pre-amplified in amplifier 7, and mixed with the microwave source power in triple-balanced mixer 5, Pacific Microwave Model M3001HA. The modulated source power is combined with the un-modulated source power through a two-way power combiner 6. A line stretcher 12 in the path of the un-modulated source power controls the depth of modulation of the combined output by adjusting for constructive or destructive phase summation. The amplitude-

modulated 10 GHz signal is mixed with a signal from an 85-GHz source oscillator 8 in mixer 9 and high-pass filtered in waveguide filter 13 to reject the 75 GHz image band. The resultant, amplitude-modulated 95 GHz signal contains spectral components between 93 and 97 GHz, assuming unfiltered 1.25 Gbps modulation. A rectangular WR-10 waveguide output of the high pass filter is converted to a circular waveguide 14 and fed to a circular horn 15 of 4 inches diameter, where it is transmitted into free space. The horn projects a half-power beam width of 2.2 degrees.

The circuit diagram for the receiver is shown in FIG. 2. The antenna is a circular horn <sup>15R</sup> of 6 inches in diameter, fed from a waveguide unit 14R consisting of a circular W-band waveguide and a circular-to-rectangular waveguide converter which translates the antenna feed to WR-10 waveguide which in turn feeds heterodyne receiver module 2R. This module consists of a monolithic millimeter-wave integrated circuit (MMIC) low-noise amplifier spanning 89-99 GHz, a mixer with a two-times frequency multiplier at the LO port, and an IF amplifier covering 5-15 GHz. These receivers are available from suppliers such as Lockheed Martin. The local oscillator 8R is a cavity-tuned Gunn oscillator operating at 42.0 GHz (Spacek Model GQ410K), feeding the mixer in module R2 through a 6 dB attenuator <sup>7R</sup>. A bias tee <sup>6R</sup> at the local oscillator input supplies DC power to receiver module 2R. A voltage regulator circuit using a National Semiconductor LM317 integrated circuit regulator supplies +3.3V through bias tee <sup>6R</sup>. An IF output of the heterodyne receiver module 2R is filtered at 6-12 GHz using bandpass filter <sup>3R</sup> from K&L Microwave. Receiver 4R which is an HP Herotek Model DTM 180AA diode detector, measures total received power. The voltage output from the diode detector is amplified in two-cascaded microwave amplifiers 5R from MiniCircuits, Model 2FL2000. The baseband output is carried on coax cable to a media converter for conversion to optical fiber, or to a Bit Error-Rate Tester (BERT) 10R.

In the laboratory, this embodiment has demonstrated a bit-error rate of less than  $10^{-12}$  for digital data transmission at 1.25 Gbps. The BERT measurement unit was a Microwave Logic, Model gigaBERT. The oscilloscope signal for digital data received at 200 Mbps is shown in FIG. 3. At 1.25 Gbps, oscilloscope bandwidth limitations lead to the rounded bit edges seen in FIG. 4. Digital levels sustained for more than one bit period comprise

lower fundamental frequency components (less than 312 MHz) than those which toggle each period (622 MHz), so the modulation transfer function of the oscilloscope, which falls off above 500 MHz, attenuates them less. These measurement artifacts are not reflected in the bit error-rate measurements, which yield  $<10^{-12}$  bit error rate at 1.25 Gbps.

### Transceiver System

A preferred embodiment of the present invention is described by reference to FIGS. 5 to 7. The link hardware consists of a millimeter-wave transceiver pair including a pair of millimeter-wave antennas and a microwave transceiver pair including a pair of microwave antennas. The millimeter wave transmitter signal is amplitude modulated and single-sideband filtered, and includes a reduced-level carrier. The receiver includes a heterodyne mixer, phase-locked intermediate frequency (IF) tuner, and IF power detector.

Millimeter-wave transceiver A (FIGS. 5A and 5B) transmits at 92.3-93.2 GHz as shown at 60 in FIG. 7A and receives at 94.1-95.0 GHz as shown at 62, while millimeter-wave transmitter B (FIGS. 6A and 6B) transmits at 94.1-95.0 GHz as shown at 64 in FIG. 7B and receives at 92.3-93.2 GHz as shown at 66.

### Millimeter Wave Transceiver A

As shown in FIG. 5A in millimeter-wave transceiver A, transmit power is generated with a cavity-tuned Gunn diode 21 resonating at 93.15 GHz. This power is amplitude modulated using two balanced mixers in an image reject configuration 22, selecting the lower sideband only. The source 21 is modulated at 1.25 Gbps in conjunction with Gigabit-Ethernet standards. The modulating signal is brought in on optical fiber, converted to an electrical signal in media converter 19 (which in this case is an Agilent model HFCT-5912E) and amplified in preamplifier 20. The amplitude-modulated source is filtered in a 900 MHz-wide passband between 92.3 and 93.2 GHz, using a bandpass filter 23 on microstrip. A portion of the source oscillator signal is picked off with coupler 38 and combined with the lower sideband in power combiner 39, resulting in the

transmitted spectrum shown at 60 in FIG. 7A. The combined signal propagates with horizontal polarization through a waveguide 24 to one port of an orthomode transducer 25, and on to a two-foot diameter Cassegrain dish antenna 26, where it is transmitted into free space with horizontal polarization.

The receiver unit at Station A as shown on FIGS 5B1 and 5B2 is fed from the same Cassegrain antenna 26 as is used by the transmitter, at vertical polarization (orthogonal to that of the transmitter), through the other port of the orthomode transducer 25. The received signal is pre-filtered with bandpass filter 28A in a passband from 94.1 to 95.0 GHz, to reject back scattered return from the local transmitter. The filtered signal is then amplified with a monolithic MMW integrated-circuit amplifier 29 on indium phosphide, and filtered again in the same passband with bandpass filter 28B. This twice filtered signal is mixed with the transmitter source oscillator 21 using a heterodyne mixer-downconverter 30, to an IF frequency of 1.00-1.85 GHz, giving the spectrum shown at 39A in FIG. 7A. A portion of the IF signal, picked off with coupler 40, is detected with integrating power detector 35 and fed to an automatic gain control circuit 36. The fixed-level IF output is passed to the next stage as shown in FIG. 5B2. Here a quadrature-based (I/Q) phase-locked synchronous detector circuit 31 is incorporated, locking on the carrier frequency of the remote source oscillator. The loop is controlled with a microprocessor 32 to minimize power in the "Q" channel while verifying power above a set threshold in the "I" channel. Both "I" and "Q" channels are lowpass-filtered at 200 MHz using lowpass filters 33A and 33B, and power is measured in both the "I" and "Q" channels using square-law diode detectors 34. The baseband mixer 38 output is pre-amplified and fed through a media converter 37, which modulates a laser diode source into a fiber-optic coupler for transition to optical fiber transmission media.

#### Transceiver B

As shown in FIG. 6A in millimeter-wave transceiver B, transmit power is generated with a cavity-tuned Gunn diode 41 resonating at 94.15 GHz. This power is amplitude modulated using two balanced mixers in an image reject configuration 42, selecting the upper sideband only. The source 41 is modulated at 1.25 Gbps in conjunction with

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Gigabit-Ethernet standards. The modulating signal is brought in on optical fiber as shown at 80, converted to an electrical signal in media converter 60, and amplified in preamplifier 61. The amplitude-modulated source is filtered in a 900 MHz-wide passband between 94.1 and 95.0 GHz, using a bandpass filter 43 on microstrip. A portion of the source oscillator signal is picked off with coupler 48 and combined with the higher sideband in power combiner 49, resulting in the transmitted spectrum shown at 64 in FIG. 7B. The combined signal propagates with vertical polarization through a waveguide 44 to one port of an orthomode transducer 45, and on to a Cassegrain dish antenna 46, where it is transmitted into free space with vertical polarization.

(FIG. 6B1)

The receiver is fed from the same Cassegrain antenna 46 as the transmitter, at horizontal polarization (orthogonal to that of the transmitter), through the other port of the orthomode transducer 45. The received signal is filtered with bandpass filter 47A in a passband from 92.3 to 93.2 GHz, to reject backscattered return from the local transmitter. The filtered signal is then amplified with a monolithic MMW integrated-circuit amplifier on indium phosphide 48, and filtered again in the same passband with bandpass filter 47B. This twice filtered signal is mixed with the transmitter source oscillator 41 using a heterodyne mixer-downconverter 50, to an IF frequency of 1.00-1.85 GHz, giving the spectrum shown at 39B in FIG. 7B. A portion of the IF signal, picked off with coupler 62, is detected with integrating power detector 55 and fed to an automatic gain control circuit 56. The fixed-level IF output is passed to the next stage as shown on FIG. 6B2. Here a quadrature-based (I/Q) phase-locked synchronous detector circuit 51 is incorporated, locking on the carrier frequency of the remote source oscillator. The loop is controlled with a microprocessor 52 to minimize power in the "Q" channel while verifying power above a set threshold in the "I" channel. Both "I" and "Q" channels are lowpass-filtered at 200 MHz using a bandpass filters 53A and 53B, and power is measured in each channel using a square-law diode detector 54. The baseband mixer 58 output is pre-amplified and fed through a media converter 57, which modulates a laser diode source into a fiber-optic coupler for transition to optical fiber transmission media.

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## Very Narrow Beam Width

A dish antenna of two-foot diameter projects a half-power beam width of about 0.36 degrees at 94 GHz. The full-power beamwidth (to first nulls in antenna pattern) is narrower than 0.9 degrees. This suggests that up to 400 independent beams could be projected azimuthally around an equator from a single transmitter location, without mutual interference, from an array of 2-foot dishes. At a distance of ten miles, two receivers placed 800 feet apart can receive independent data channels from the same transmitter location. Conversely, two receivers in a single location can discriminate independent data channels from two transmitters ten miles away, even when the transmitters are as close as 800 feet apart. Larger dishes can be used for even more directivity.

## Rigid Antenna Support

A communication beam having a half-power beam width of only about 0.36 degrees requires an extremely stable antenna support. Prior art antenna towers such as those used for microwave communication typically are designed for angular stability of about 0.6 to 1.1 degrees or more. Therefore, the present invention requires much better control of beam direction. For good performance the receiving antenna should be located at all times within the half power foot print of the transmitted beam. At 10 miles the half power footprint of a 0.36-degree beam is about 332 feet. During initial alignment the beam should be directed so that the receiving transceiver antenna is located approximately at the center of the half-power beam width footprint area. The support for the transmitter antenna should be rigid enough so that the beam direction does not change enough so that the receiving transceiver antenna is outside the half-power footprint. Thus, in this example the transmitting antenna should be directionally stable to within  $\pm 0.18$  degrees.

This rigid support of the antenna not only assures continued communication between the two transceivers as designed but the narrow beam widths and rigid antenna support reduces the possibility of interference with any nearby links operating in the same spectral band.

Many rigid supports can be used for maintaining antenna alignment. Applicants have performed computer model studies of potential supports using WindCalculator software provided by Andrew Corp. with offices in St. Orland Park, Illinois and tower bending software know as Beam Calc.xls developed by WarrenDesignVision Company. For example, these calculations show that a solidly mounted 12-inch diameter 40 feet tall hollow carbon steel (one-half inch wall thickness) monopole tower having a 0.7 meter high, 1 meter diameter radome at the top (a two-foot diameter antenna is enclosed in the radome) would suffer deflections of about 0.74 degrees in a 90 mile per hour steady wind. FIG. 10 shows the effect of a 0.74-degree deflection of a 0.36-degree beam. The 0.74 degree deflection moves the beam axis 682 feet at 10 miles so that the receive antenna is clearly outside the beam 332 foot half power footprint. This angular variation would almost certainly disrupt communication between the millimeter wave links described above. However, similar calculations made for a solidly mounted 24-inch diameter, 40 feet tall hollow carbon steel monopole tower shows that the deflection in a 90 mile per hour wind would be only 0.11 degrees. This structure is shown in ~~FIG. 10~~ <sup>FIGS. 9 and 9A.</sup>

The 24-inch tube 700 supports radome 720 enclosing antenna 740, antenna mount 760 and transceiver 750. Flange 710 is welded to the bottom of tube 700 and is bolted with bolts 800 encased in reinforced concrete base 820 which is buried mostly below ground level 730. This would assure with substantial margin that the communication between the two transceivers would not be disrupted due to beam directional deviations. Therefore, in preferred embodiments, antennas of about 2 feet diameter are mounted on solidly mounted reinforced concrete monopole towers having heights of 40 feet or less as shown in FIG. 9. The reader should note that many other potential rigid structures could be designed to support the antennas with the directional stability required under the general guidelines outlined above. For example, antennas could be rigidly mounted on the side or top of stable buildings. Steel trussed towers could be used or monopoles with high tension guide wires. In each case however the designer should determine using reliable codes or actual testing that these alternate supports are adequate to maintain the needed directional stability.

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It is also possible to take care of directional stability using active antenna directional control with a feedback control system. However, such a system although feasible will typically be much more expensive than the rigid supports of the type described above.

#### Backup Microwave Transceiver Pair

During severe weather conditions data transmission quality will deteriorate at millimeter wave frequencies. Therefore, in preferred embodiments of the present invention a backup communication link is provided which automatically goes into action whenever a predetermined drop-off in quality transmission is detected. A preferred backup system is a microwave transceiver pair operating in the 10.7-11.7 GHz band. This frequency band is already allocated by the FCC for fixed point-to-point operation. FCC service rules parcel the band into channels of 40-MHz maximum bandwidth, limiting the maximum data rate for digital transmissions to 45 Mbps full duplex. Transceivers offering this data rate within this band are available off-the-shelf from vendors such as Western Multiplex Corporation (Models Lynx DS-3, Tsunami 100BaseT), and DMC Stratex Networks (Model DXR700 and Altium 155). The digital radios are licensed under FCC Part 101 regulations. The microwave antennas are Cassegrain dish antennas of 24-inch diameter. At this diameter, the half-power beamwidth of the dish antenna is 3.0 degrees, and the full-power beamwidth is 7.4 degrees, so the risk of interference is higher than for MMW antennas. To compensate this, the FCC allocates twelve separate transmit and twelve separate receive channels for spectrum coordination within the 10.7-11.7 GHz band.

Sensing of a millimeter wave link failure and switching to redundant microwave channel is an existing automated feature of the network routing switching hardware available off-the-shelf from vendors such as Cisco, Foundry Networks and Juniper Networks.

#### Narrow Beam Width Antennas

The narrow antenna beam widths afforded at millimeter-wave frequencies allow for geographical portioning of the airwaves, which is impossible at lower frequencies. This fact eliminates the need for band parceling (frequency sharing), and so enables wireless



communications over a much larger bandwidth, and thus at much higher data rates, than were ever previously possible at lower RF frequencies.

The ability to manufacture and deploy antennas with beam widths narrow enough to ensure non-interference, requires mechanical tolerances, pointing accuracies, and electronic beam steering/tracking capabilities, which exceed the capabilities of the prior art in communications antennas. An preferred antenna for long-range communication at frequencies above 70 GHz has gain in excess of 50 dB, 100 times higher than direct-broadcast satellite dishes for the home, and 30 times higher than high-resolution weather radar antennas on aircraft. However, where interference is not a potential problem, antennas with dB gains of 40 to 45 may be preferred.

Most antennas used for high-gain applications utilize a large parabolic primary collector in one of a variety of geometries. The prime-focus antenna places the receiver directly at the focus of the parabola. The Cassegrainian antenna places a convex hyperboloidal secondary reflector in front of the focus to reflect the focus back through an aperture in the primary to allow mounting the receiver behind the dish. (This is convenient since the dish is typically supported from behind as well.) The Gregorian antenna is similar to the Cassegrainian antenna, except that the secondary mirror is a concave ellipsoid placed in back of the parabola's focus. An offset parabola rotates the focus away from the center of the dish for less aperture blockage and improved mounting geometry. Cassegrainian, prime focus, and offset parabolic antennas are the preferred dish geometries for the MMW communication system.

A preferred primary dish reflector is a conductive parabola. The preferred surface tolerance on the dish is about 15 thousandths of an inch (15 mils) for applications below 40 GHz, but closer to 5 mils for use at 94 GHz. Typical hydroformed aluminum dishes give 15-mil surface tolerances, although double-skinned laminates (using two aluminum layers surrounding a spacer layer) could improve this to 5 mils. The secondary reflector in the Cassegrainian geometry is a small, machined aluminum "lollipop" which can be made to 1-mil tolerance without difficulty. Mounts for secondary reflectors and receiver

waveguide horns preferably comprise mechanical fine-tuning adjustment for in-situ alignment on an antenna test range.

#### Flat Panel Antenna

Another preferred antenna for long-range MMW communication is a flat-panel slot array antenna such as that described by one of the present inventors and others in U.S. Patent No. 6,037,908, issued 14 March 2000 which is hereby incorporated herein by reference. That antenna is a planar phased array antenna propagating a traveling wave through the radiating aperture in a transverse electromagnetic (TEM) mode. A communications antenna would comprise a variant of that antenna incorporating the planar phased array, but eliminating the frequency-scanning characteristics of the antenna in the prior art by adding a hybrid traveling-wave/corporate feed. Flat plates holding a 5-mil surface tolerance are substantially cheaper and easier to fabricate than parabolic surfaces. Planar slot arrays utilize circuit-board processing techniques (e.g. photolithography), which are inherently very precise, rather than expensive high-precision machining.

#### Coarse and Fine Pointing

Pointing a high-gain antenna requires coarse and fine positioning. Coarse positioning can be accomplished initially using a visual sight such as a bore-sighted rifle scope or laser pointer. The antenna is locked in its final coarse position prior to fine-tuning. The fine adjustment is performed with the remote transmitter turned on. A power meter connected to the receiver is monitored for maximum power as the fine positioner is adjusted and locked down.

At gain levels above 50 dB, wind loading and tower or building flexure can cause an unacceptable level of beam wander. A flimsy antenna mount could not only result in loss of service to a wireless customer; it could inadvertently cause interference with other licensed beam paths. In order to maintain transmission only within a specific "pipe," some method for electronic beam steering may be required.

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## Beam Steering

Phased-array beam combining from several ports in the flat-panel phased array could steer the beam over many antenna beam widths without mechanically rotating the antenna itself. Sum-and-difference phase combining in a mono-pulse receiver configuration locates and locks on the proper "pipe." In a Cassegrainian antenna, a rotating, slightly unbalanced secondary ("conical scan") could mechanically steer the beam without moving the large primary dish. For prime focus and offset parabolas, a multi-aperture (e.g., quad-cell) floating focus could be used with a selectable switching array. In these dish architectures, beam tracking is based upon maximizing signal power into the receiver. In all cases, the common aperture for the receiver and transmitter ensures that the transmitter, as well as the receiver, is correctly pointed.

## Typical Installation

FIG. 8 is a map layout of a proposed application of the present invention. This map depicts a sparsely populated section of the island, Maui in Hawaii. Shown are communication facility 70 which is connected to a major communication trunk line from a communication company's central office 71, a technology park 72 located about 2 miles from facility 70, a relay station 76 located about 6 miles from facility 70 and four large ocean-front hotels 78 located about 3 miles from relay station 76. Also shown is a mountaintop observatory 80 located 13 miles from facility 70 and a radio antenna tower 79 located 10 miles from facility 70. As indicated in FIG. 8, the angular separation between the radio antenna and the relay station is only 4.7 degrees. Four type-A transceiver units are positioned at facility 70, each comprising a transmitter and receiver unit as described in FIGS. 5A and 5B. These units are directed at corresponding type-B transceiver units positioned at the technology park, the relay station, the observatory, and the radio tower. Millimeter wave transceiver units with back-up microwave units as described above are also located at the hotels and are in communication with corresponding units at the relay station. In a preferred embodiment the 1.25 GHz spectrum is divided among the four hotels so that only one link needs to be provided between facility 70 and relay station 76. This system can be installed and operating within a period of about one month and providing the most modern communication links

to these relatively isolated facilities. The cost of the system is a very small fraction of the cost of providing fiber optic links offering similar service.

The microwave backup links operate at approximately eight times lower frequency (8 times longer wavelength) than the millimeter wave link. Thus, at a given size, the microwave antennas have broader beam widths than the millimeter-wave antennas, again wider by about 8 times. A typical beam width from a 2-foot antenna is about 7.5 degrees. This angle is wider than the angular separation of four service customers (hotels) from the relay tower and it is wider than the angular separation of the beam between the relay station and the radio antenna. Specifically, the minimum angular separation between hotels from the relay station is 1.9 degrees. The angular separation between receivers at radio antenna tower 79 and relay station 76 is 4.7 degrees as seen from a transmitter at facility 70. Thus, these microwave beams cannot be separated spatially; however, the FCC Part 101 licensing rules mandate the use of twelve separate transmit and twelve separate receive channels within the microwave 10.7 to 11.7 GHz band, so these microwave beams can be separated spectrally. Thus, the FCC sponsored frequency coordination between the links to individual hotels and between the links to the relay station and the radio antenna will guarantee non-interference, but at a much reduced data rate. The FCC has appointed a Band Manager, who oversees the combined spatial and frequency coordination during the licensing process.

#### Other Wireless Techniques

Any millimeter-wave carrier frequency consistent with U.S. Federal Communications Commission spectrum allocations and service rules, including MMW bands currently allocated for fixed point-to-point services at 57-64 GHz, 71-76 GHz, 81-86 GHz, and 92-100 GHz, can be utilized in the practice of this invention. Likewise any of the several currently-allocated microwave bands, including 5.2-5.9 GHz, 5.9-6.9 GHz, 10.7-11.7 GHz, 17.7-19.7 GHz, and 21.2-23.6 GHz can be utilized for the backup link. The modulation bandwidth of both the MMW and microwave channels can be increased, limited again only by FCC spectrum allocations. Also, any flat, conformal, or shaped antenna capable of transmitting the modulated carrier over the link distance in a means

consistent with FCC emissions regulations can be used. Horns, prime focus and offset parabolic dishes, and planar slot arrays are all included.

Transmit power may be generated with a Gunn diode source, an injection-locked amplifier or a MMW tube source resonating at the chosen carrier frequency or at any sub-harmonic of that frequency. Source power can be amplitude, frequency or phase modulated using a PIN switch, a mixer or a biphase or continuous phase modulator. Modulation can take the form of simple bi-state AM modulation, or can involve more than two symbol states; e.g. using quantized amplitude modulation (QAM). Double-sideband (DSB), single-sideband (SSB) or vestigial sideband (VSB) techniques can be used to pass, suppress or reduce one AM sideband and thereby affect bandwidth efficiency. Phase or frequency modulation schemes can also be used, including simple FM, bi-phase, or quadrature phase-shift keying (QPSK). Transmission with a full or suppressed carrier can be used. Digital source modulation can be performed at any data rate in bits per second up to eight times the modulation bandwidth in Hertz, using suitable symbol transmission schemes. Analog modulation can also be performed. A monolithic or discrete-component power amplifier can be incorporated after the modulator to boost the output power. Linear or circular polarization can be used in any combination with carrier frequencies to provide polarization and frequency diversity between transmitter and receiver channels. A pair of dishes can be used instead of a single dish to provide spatial diversity in a single transceiver as well.

The MMW Gunn diode and MMW amplifier can be made on indium phosphide, gallium arsenide, or metamorphic InP-on-GaAs. The MMW amplifier can be eliminated completely for short-range links. The mixer/downconverter can be made on a monolithic integrated circuit or fabricated from discrete mixer diodes on doped silicon, gallium arsenide, or indium phosphide. The phase lock loop can use a microprocessor-controlled quadrature (I/Q) comparator or a scanning filter. The detector can be fabricated on silicon or gallium arsenide, or can comprise a heterostructure diode using indium antimonide.

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The backup transceivers can use alternative bands 5.9-6.9 GHz, 17.7-19.7 GHz, or 21.2-23.6 GHz; all of which are covered under FCC Part 101 licensing regulations. The antennas can be Cassegrainian, offset or prime focus dishes, or flat panel slot array antennas, of any size appropriate to achieve suitable gain.

#### Digital Service Link for Remote Luxury Hotel

FIG. 11 is a schematic depiction of an important preferred application of the present invention. This drawing shows an in-room communication network 100 for one of the luxury hotels 78 shown in FIG. 8. In this example, the existing internal communication network for the hotel included several sets of twisted pairs feeding from a circuit board on the ground floor of the hotel to each guest room of the hotel and all other important rooms including conference rooms. The existing network utilized one of the twisted pairs to each room to provide conventional analog telephone service through the local telephone company. The existing network also included a coaxial cable network providing cable television to each room. For this preferred embodiment the existing telephone service and the cable television service was not disturbed.

Network 100 provides for the hotel guests in this embodiment high-speed data communication at rates of 9 Mbps through transceiver 78A, relay station 76 and facility 70 to the Internet. As discussed above the communication channel between facility 70 and relay station 76 is at a rate of 1.25 Gbps. The channel between station 76 and the hotel transceiver 78 is at a rate of 622 Gbps. Each twisted pair to each room is no longer than 1000 feet so data rates of about 8 Mbps can be provided with off-the-shelf VDSL equipment as described below. In this preferred embodiment the gigabit switch 102 is a switch/router Model Big Iron 4000 available from Foundry Networks, Inc with offices in San Jose, California. Three DSL concentrators <sup>106A, 106B, and 106C</sup> ~~106A, B and C~~ are Copper Mountain Networks, Inc. (offices in Palo Alto, California) Model Copper Edge 2000 concentrators. These concentrators provide multiplexing to concentrate the communication from each of 250 hotel rooms into the hotel's 622 Mbps link to the Internet. DLS modems 110, which are available from many suppliers such as Alcatel NV with offices in Rijswijk in the Netherlands or Infinilink Corporation with offices in Irvine California (Model i510),

provide downstream data at a rate of 8.192 Mbps and upstream data rates at 800 Kbps for equipment such as CPU 112. Although each room has a capacity of about 8 Mbps, due to the extremely low duty factors applicable to communication systems such as this, the 622 Mbps hotel is considered by Applicants to be completely adequate. In the future if usage expands, the 622 <sup>46ps</sup> Gbps link can be easily improved to whatever speed is needed. This can be done by giving Hotel 78A a larger share of the 1.25 Gbps going into relay station 76 or an additional millimeter wave link can be established.

As stated above, this embodiment leaves in place the hotel's existing telephone system and cable television system. Persons skilled in the art will recognize that the telephone can easily be incorporated into the present system using DSL technology as discussed in the background section of this specification. It is also possible the use the existing cable television lines to carry the digital data to each room. Furthermore, it is also possible to use an Ethernet to carry the digital data to each room.

#### Ethernet Service

The embodiment described above can be implemented quickly and effectively using existing communication wiring. It was developed specifically to take advantage of old installed wiring so in many cases it will be the obvious choice for providing high downstream data rate service. However, there are some disadvantages with the DSL alternative. First, the cost of the equipment is relatively high compared to other data network equipment. Second, in some cases fast two-way communication is needed. The DSL technology was developed to connect people with the Internet. In some cases a connection for all users to the Internet may not be needed or desirable. Also, many facilities are equipped with more advanced communication wiring so other alternatives are available without large expenditures for wiring.

#### High Data Rate Service to Ethernet Network at Remote Luxury Hotel

FIG. 12 is a drawing showing an embodiment of the present invention for providing high data rate service for guests at a luxury hotel at an estimated cost of about 10 percent of the system described above using the DSL equipment with much faster two-way

communication rates for the individual users. In this embodiment relay station 76 transmits data to the hotel transceiver 78A at the full 1.25 Gbps rate. In this case gigabit switch 102 is a Cisco Model 3812 switch which is fed by three Ethernet switches <sup>106A, 106B, and 106C</sup> ~~106A, B and C~~ which are Cisco Model 3548 switches each of which distributes the incoming data to digital equipment 112 of up to 48 users, each at 100 Mbps two-way. (Alternatively, 3Com 4900 Super Stack switch and 3Com 2900Super Stack II switches could be used in lieu of the Cisco switches.) Communication wiring to the guestrooms is assumed to be twisted pairs and distances between switches and the rooms are within specifications for the 100 Mbps service. With this communication system Communication Facility 70 could provide high data rate communication service such as video-on-demand to each of the guests in the hotel. High-speed Internet service could also be provided.

#### High Speed Data to Work Spaces

FIG. 13 shows an Ethernet Network very similar to the FIG.12 embodiment, but the network is serving up to 144 workspaces. This could represent a business with about 100 employees at a remote location needing the high-speed communication among them selves and to another location such as the business headquarters. In this case the equipment is the same as that described above with reference to FIG. 12, the users are workers and not guests.

#### Other Ethernet Networks

As indicated in the Background section Ethernet protocols are also available at 10 Mbps and at 1000 Mbps. The present invention could be applied at these data rates and in many situations these other data rates will be preferred to the 100 Mbps rate of the two embodiments described in detail above.

#### Multi-Protocol Data Aggregation and SONET

FIG. 14 schematically shows a preferred embodiment with an aggregation unit and one or more high-speed wireless links providing access (to the optical core) and traffic grooming for a wide variety of different telecommunications protocols at a customer's premises.



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Aggregation unit 210 grooms telecommunication traffic 220 from customer premises 230. Telecommunication traffic 220 comprises one or more of xDSL<sup>250</sup>, voice 252, OC-3/12 (TDM, ATM, IP) 254, Ethernet 256, Gigabit Ethernet 258, SAN (Storage Area Network) 260, DS1 262, or DS3 264. Aggregation unit 210 can be, for example, a network hardware unit by the name of C7 (which is short for Calix C7 Optical Access Platform) that is manufactured by Calix in Petaluma, California. Telecommunication traffic 220 which has been groomed by aggregation unit 210 is transported to an optical core 270 via one or more high-speed wireless links 280 (such as shown in FIGS. 5A through 6B2 operating at, for example, OC-12 (622.08 MB/S). Assuming the one or more high-speed wireless links 280 comprise at least two high-speed wireless links, then the at least two high-speed wireless links can be arranged to form part of a ring-structured network, thus enabling the redundancy and failure tolerance that ring-structured networks can provide.

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FIG. 15 schematically shows a preferred embodiment with an aggregation unit and several wireless gigabit links, such as the link shown in ~~FIG. 5A~~<sup>FIGS.</sup> 5A through 6B2, providing access (to a SONET ring) and traffic grooming for a wide variety of different telecommunications protocols at a variety of different customer's premises. In this embodiment, aggregation unit 310 sends data to and receives data from gigabit wireless links 320, 324 and 326. Aggregation unit 310 also communicates with SONET ring 350. Gigabit wireless links 320, 324 and 326 communicate with gigabit Ethernet routers/switches 330, 334 and 336 respectively. Gigabit Ethernet router/switch 330 located at large business premises 340 can process traffic (via link 322) from yet another location at small business premises 342 which contains 10/100 Megabit Ethernet router/switch 332. Similarly, gigabit Ethernet router/switch 334 located at building 344 handles traffic from campus ring 360 which links buildings 344, 364 and 366. Furthermore, gigabit Ethernet router/switch 336 handles traffic from MTU (multi-tenant unit) building 346.

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While the above description contains many specifications, the reader should not construe these as a limitation on the scope of the invention, but merely as exemplifications of

preferred embodiments thereof. For example, the full allocated MMW band referred to in the description of the preferred embodiment described in detail above along with state of the art modulation schemes may permit transmittal of data at rates exceeding 10 Gbits per second. Such data rates would permit links compatible with 10-Gigabit Ethernet, a standard that is expected to become practical within a year. The present invention is especially useful in those locations where fiber optics communication is not available and the distances between communications sites are less than about 15 miles but longer than the distances that could be reasonably served with free space laser communication devices. Ranges of about 1 mile to about 10 miles are ideal for the application of the present invention. However, in regions with mostly clear weather the system could provide good service to distances of 20 miles or more. It is also feasible to use the hotels already installed coaxial cable TV network to provide the Ethernet service into each hotel room. Accordingly the reader is requested to determine the scope of the invention by the appended claims and their legal equivalents, and not by the examples given above.

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